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ON THE ABSOLUTE MEASUREMENT OF ALTERNATING CURRENTS AND THE CALIBRATION OF THERMOCOUPLES IN THE DECIMETER-WAVE-RANGE UP TO 500 MEGACYCLES PER SECOND

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Zusammenfassung

Für die absolute Messung von Wechselströmen im Frequenzgebiet bis 60 Megahertz wird Gebrauch gemacht von Diodenvoltmetern zur Messung von Wechselspannungen über bekannten Impedanzen. Unter Berücksichtigung der Messgenauigkeit dieser Diodenvoltmeter (etwa 1% bei 60 Megahertz) wird gezeigt dass Thermokreuze verschiedener Konstruktion bis 60 Megahertz den Absolutwert eines Wechselstroms, unter Benutzung ihrer Gleichstrom-Eichkurve mit einem Fehler unter etwa 2% anzeigen. Bei Frequenzen bis 500 Megahertz wird zur Eichung von Thermokreuzen und zur absoluten Messung von Wechselströmen ein Hitzdrahtluftthermometer nach A. Scheibe benutzt. Mit dieser Vorrichtung und einer geeigneten Lecherbrückenanordnung werden Wechselströme von einigen mA bei 500 Megahertz innerhalb 5% und bei 325 Megahertz innerhalb 1% gemessen. Die Anzeigefehler besonders konstruierter Thermokreuze liegen ebenfalls innerhalb dieser Grenzen.

I. *Measurements at frequencies up to 60 megacycles/sec.* The basic idea of the measurements of currents at frequencies up to 60 megacycles/sec is this: We have diodevoltmeters, the calibration of which, taken at 500 cycles, holds within 1% down to 5 m wavelength. On the other hand, we have measured (bibliogr. nr. 10) the impedance of circuits consisting of a self-inductance parallel to a capacity down to 1 m wavelength, also within 1%, requiring an absolutely calibrated variable condenser and a relatively calibrated voltmeter (e.g. diode-voltmeter). Hence, the volts across a known impedance may be measured. Connecting an ammeter, e.g. a thermocouple, in series

with the known impedance, this ammeter may be absolutely calibrated down to 5 m wavelength.

The circuit of the diode-voltmeter, used in the measurements, is shown in Fig. 1. The diode is a so-called acorn tube construction

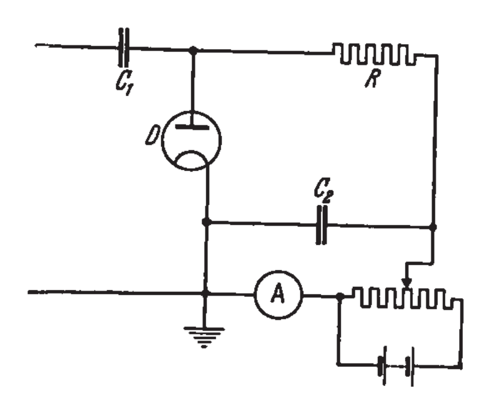


Fig. 1. Diode Voltmeter. D acorn diode. A microammeter. C_1 condenser of 100 $\mu\mu F$. R resistance of 2.10^5 Ohms. C_2 condenser of 10.000 $\mu\mu F$.

(Philips type 4674), having a capacity of about $C_1 = 1{,}5\ \mu\mu F$ between cathode and anode. Although the wiring is as short as possible, there is always a certain length of wire between the two ends of a self-induction coil, across which we wish to measure the alternating voltage and the electrodes of the said diode. Considering, that the inductance of 1 cm length of straight wire is of the order of 10^{-8} H e n r y, a total inductance L_1 of $6 \,.\, 10^{-8}$ H e n r y for the lengths of wire, connecting the diode across the coil, constitutes a reasonable value. The voltage to be measured is called E (across the coil) and the voltage between the electrodes of the diode is called e. Then $E/e = 1/(1 - \omega^2 L_1 C_1)$, where ω is 2π times the frequency in cycles/sec. With the above values we get at $\omega = 2\pi \,.\, 60$ megacycles/sec. $\omega^2 . L_1 C_1 = 4\pi^2 \,.\, 36 \,.\, 10^{14} \,.\, 6 \,.\, 10^{-8} \,.\, 1{,}5 \,.\, 10^{-12} = 1{,}3 \,.\, 10^{-2}$. Hence, as the diode reacts to the voltage e and not to E, an inaccuracy of somewhat more than 1% arises from the length of the voltmeter connections. The distance between cathode and anode of the diode is only 0,1 mm and electron transit times do not alter the rectifying properties of a diode with this small distance up to 300 megacycles/sec within 1%. We may be sure, then, that a calibration curve of the diode voltmeter, properly taken at, say, 500 cycles/sec, will hold good up to 60 megacycles/sec within about 1%.

As an impedance, we use a circuit, consisting of a variable condenser C, connected in parallel to an inductance coil L (Fig. 2). The

variable condenser scale is calibrated at 500 cycles/sec, one scale division corresponding to about 0,15 $\mu\mu F$. One tenth of a scale division may be read. This circuit is connected to a generator of alternating current by way of a coil of one or two turns (Fig. 2) and a very small series condenser C_2 (0,1 $\mu\mu F$). The current, flowing through the circuit is hence independent of its impedance, as long as this is small, compared with the impedance of the small series condenser. Across the circuit, parallel to the inductance coil, the diode voltmeter V measures the voltage.

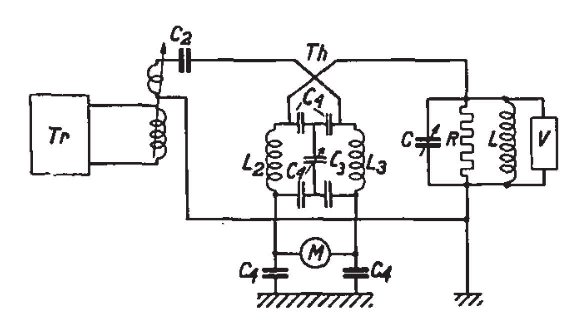


Fig. 2. Apparatus for calibrating thermocouples up to about 60 megacycles/sec. *Tr* transmitter. C_2 condenser of 0,1 $\mu\mu F$. *Th* thermocouple to be calibrated. C_4 condensers of 10.000 $\mu\mu F$. Circuit, consisting of equal inductance coils L_2 and L_3 and variable condenser C_3 tuned to transmitter frequency. Circuit consisting of variable condenser C with calibrated scale, resistance R and inductance L equally tuned to transmitter frequency. V diodevoltmeter of Fig. 1. M millivoltmeter measuring the thermotension of *Th*.

Tuning the circuit with the variable condenser to the frequency of the generator, a maximum voltage is indicated by the voltmeter. Let this be e_1 volts. Now the variable condenser is altered by an amount ΔC, corresponding with a voltage $e_1/\sqrt{2}$ across the inductance coil L. In this case, the impedance of the circuit in the tuned position is equal to a resistance $R = 1/\omega\ \Delta C$. A thermocouple *Th* is connected in series with the small condenser C_2. All thermocouples measured had no galvanic contact between the heating wires and the two thermoelectric wires. A small insulating pearl is used as a connecting link between them. The capacity between the heating wire and the thermowires was measured and turned out to be of the order of 0,5 $\mu\mu F$. Between the thermowires of the couple *Th* (Fig. 2) and the millivoltmeter M, which was earthed by means of block condensers C_4 of 10.000 $\mu\mu F$ each, a circuit, consisting of two equal inductances L_2 and L_3, a variable condenser C_3 and block condensers C_4 of 10.000 $\mu\mu F$ was inserted. This circuit was tuned by means of C_3 to the frequen-

cy of the transmitter. Its aim is to insert a high impedance between the thermowires and the earthed millivoltmeter M for the frequency under investigation, whereas this impedance is negligible for the d.c. provided by the thermowires to the meter M. The millivoltmeter M has to be earthed in order to prevent what is known as hand-effect: a variable indication according to the position of the observer's body relative to the apparatus. The impedance of the circuit $L_2C_3L_3$ at 60 megacycles/sec was of the order of 5000 Ohms in the tuned position of C_3. By the insertion of this circuit the flow of part of the a.c. which should heat the heating wire, to earth by way of the capacity between the heating wire and the thermojunction wires and of the aforesaid circuit is practically prevented. Every element of the circuit of Fig. 2 was enclosed in a small box, made of 1 mm plate iron, in order to prevent voltages or currents from being induced in an uncontrolled way on parts of the apparatus. Fig. 3 gives a complete view of the actual set as we used it. In the back-ground of Fig. 3 a small generator for wavelengths of 40—80 cm is shown, which was used in our experiments on these short waves, described in section II. The boxes are interconnected by copper tubes, containing the necessary conductors between them. Boxes and copper tubes are earthed. By this elaborate screening, every part of the apparatus could be touched without causing an alteration of the indications by the measuring instruments.

Two thermocouples were used, indicated Th_1 and Th_2, the construction of which is shown in Fig. 4. The results of our measurements are:

at 59,5 megac./sec. $i_{th_1}/i_{circuit} = 3{,}38 \text{ mA}/3{,}28 \text{ mA} = 1{,}03$

at 50 ,, $i_{th_2}/i_{circuit} = 5{,}65 \text{ mA}/5{,}38 \text{ mA} = 1{,}05$

Here i_{th_1} is the current through the heating wire of the thermocouple under investigation, read from the d.c. calibration of the couple. The value $i_{circ.}$ represents the a.c. through the circuit LC of Fig. 2 obtained by dividing the voltage indicated by the diode-voltmeter V (Fig. 2) by the measured impedance R of this circuit. The latter is of the order of 400 Ohms. If we take into account the actual lengths of wire between the diode and the circuit LC an error or 3% is quite possible. It may be observed, that no skineffect can occur in these thermocouples at these frequencies. In the thermocouples Th_1 and Th_2 the capacity between the heating wire and the other wires

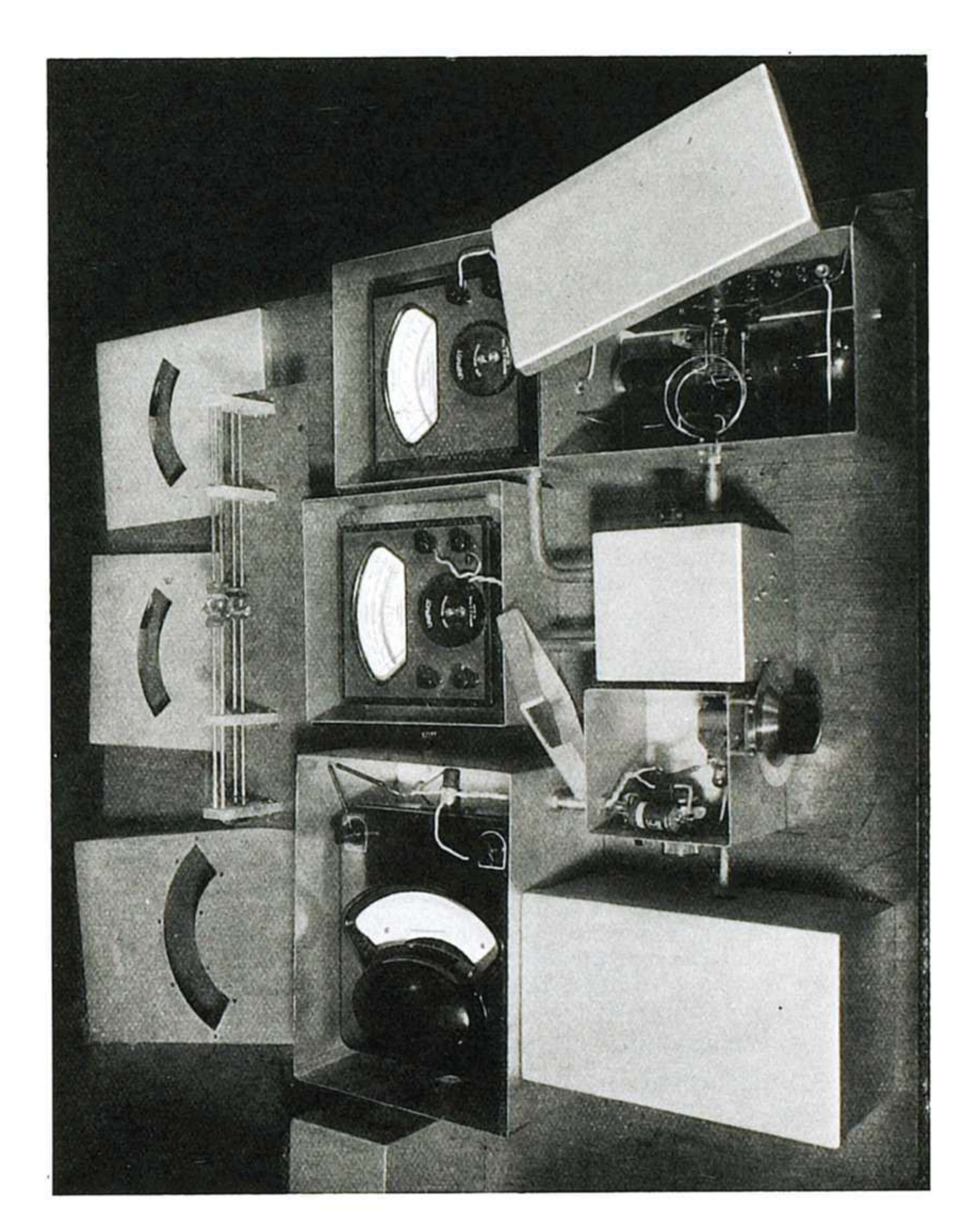


Fig. 3. Complete view of apparatus according to Fig. 2. The boxes in the foreground contain (from right to left): the push-pull transmitter, the thermocouple and its connections, the circuit LCR of Fig. 2, with the diode voltmeter V of Fig. 2 and finally the batteries of the diode voltmeter. The row of boxes in the back ground contain (from right to left): A millivoltmeter for the thermotension, a second millivoltmeter for the same purpose, the microammeter of the diode-voltmeter. In the back ground an acorn tube transmitter for wavelengths of 40—80 cm is shown.

causes a part of the a.c. to flow through the thermowires and heat them directly, thus causing an increase of the millivolts, indicated by the meter M (Fig. 2). This effect will be greater for Th_2 than for Th_1, as is seen by inspection of Fig. 4. If the impedance of the circuit $L_2C_3L_3$ were still greater with respect to R, part of this effect ought to disappear.

II. *Apparatus for measurements up to 500 megacycles/sec.* Though the highest frequency, at which the apparatus of Fig. 2 and Fig. 3 will work was rated to be higher than 80 megacylces/sec, it was felt, that a considerable extension of the frequency range would only be attained by a radical departure from this procedure. The principle of calibrating the a.c. through the thermocouple by measuring an

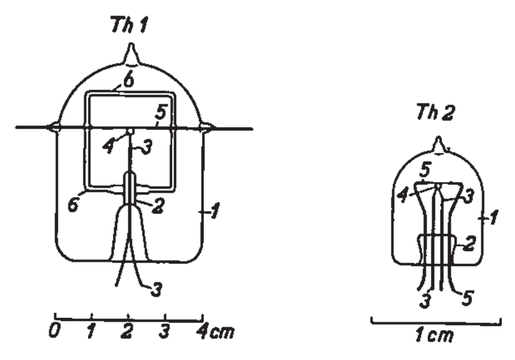


Fig. 4. Two types of thermocouples Th_1 and Th_2. A vacuum glass bulb 1 with a pinch 2 contains the heating wire 5 and the thermojunction wires 3, fastened together by means of a small pearl 4. In the couple Th_1, a glass bridge 6 is used to support the straight heating wire 5. The type Th_1 was designed by Dr. Köhler of this laboratory. The type 2 was designed by Ir. Jansen, of this laboratory, on our request.

alternating voltage was given up. Instead of this, a current measuring instrument, following a publication of A. Scheibe (Bibliography Nr. 6) was constructed. A tube 1 of polysterol (Fig. 5), an organic compound having a very low heat conductivity (much lower than glass) is closed at both ends by small plates of the same material. This material may easily be moulded by heating it a little.

A constantan wire 2 of 20 micron diameter, welded to two copper poles is fastened in the tube. A small glass tube 3 with two branches of about 3 mm internal diameter is fastened to the tube 1. This is duplicated and the two halves of the arrangement are interconnected by rubber tubes 6 and 6′ with a small capillary tube 7 inserted in 6′ and by a small capillary tube 4, containing a drop of water 5 (see

Fig. 5). The position of the water drop in the capillary tube may be observed by means of a small microscope. If a current is sent through the one tube 1, the air contained in the polysterol tube expands and causes the waterdrop to move. Now currents are sent through both tubes 1 at the same time and adjusted until the drop remains at its original position. Obviously, after a calibration of the arrangement with d.c., if an a.c. is sent through one of the tubes 1, it may be measured by a compensating d.c. through the other tube 1. As the Constantan wire of 20 micron shows no skineffect within 1% of its resistance value, up to 500 megacycles/sec. an accurate a.c. measuring

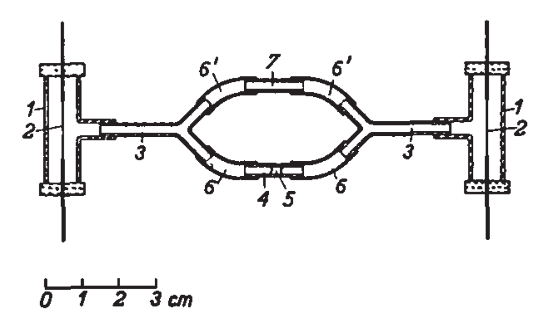


Fig. 5. Compensation ammeter for decimeter waves. Description in the text.

instrument is thus obtained. By isolating the polysterol and glass tubes by means of Asbest wire, heat losses may be further diminished. The rubber tube 6' serves with the tube 7 for equalizing air pressure differences in the tubes 1, thus keeping the waterdrop 5 at its proper

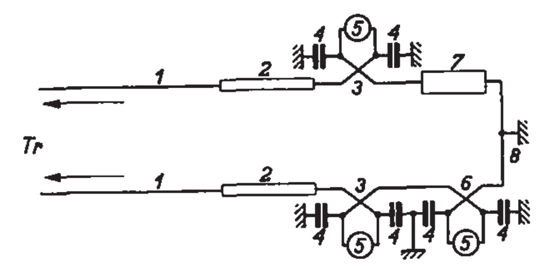


Fig. 6. Lecher bridge connections for calibrating a thermocouple 6 up to 500 megacyles/sec. Description in the text.

position. The capillary tube 7 offers a much greater resistance to the flow of air than the tube 5. An a.c. of about 5 mA may be measured to well within 1% with this instrument.

The main difficulty in calibrating thermocouples in the decimeter wave range is to ascertain, that an equal current flows through the heating wire of the couple and through the comparison instrument of Fig. 5.

This problem was solved by a L e c h e r wire arrangement (see Bibliography No. 4), shown in Figs. 6 and 7. Two copper rods of about 10 mm diameter served as L e c h e r wires 1. In series with these rods, two small fuses 2, protecting the thermocouples, two exactly equal thermocouples 3, the thermocouple 6 to be calibrated and the comparison instrument 7 are connected. The midpoint 8 of the bridge is earthed. The thermowires of the couples are earthed by means of condensers 4 of about 2000 $\mu\mu F$ and connected to millivoltmeters 5. The L e c h e r bridge is coupled to a suitable transmitter (see Fig. 3) in a way, which makes the a.c. in the heating wires of the thermocouples 3 exactly equal. The wires of the fuses have exactly equal resistance. So have the heating wire of the instrument 7 and of the thermocouple 6. The geometrical distance of the midpoint of the heating wire 7 from the point 8 is exactly equal to the distance of the midpoint of the heating wire 6 from 8. Under these circumstances, if the wavelength is not excessively short, we should expect equal

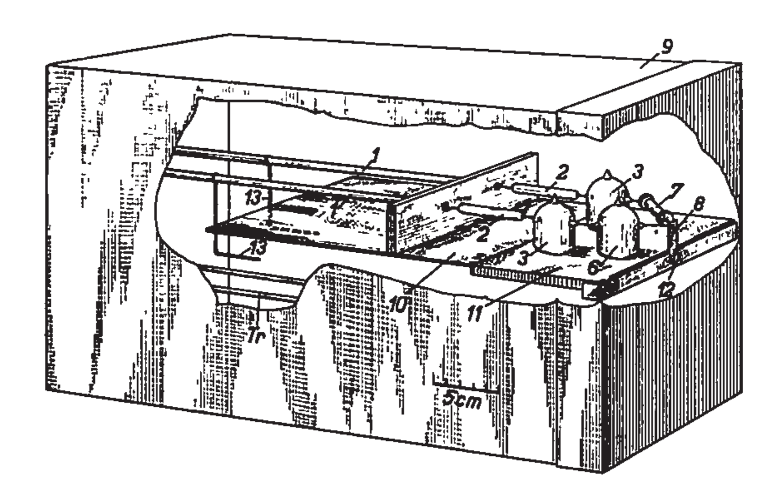


Fig. 7. View of complete apparatus according to Fig. 6. A copper box 9 is separated in two compartments by a copper plate screen 10. The lower compartment contains the transmitter *Tr* and this is coupled to the L e c h e r bridge by means of the wires 13. The bridge 1 is terminated by two fuses 2, two exactly equal thermocouples 3, a thermocouple 6 to be calibrated, an instrument 7 according to Fig. 5, mounted on a polysterol plate 11 and earthed to a copper strip 12 at 8.

heating currents in 6 and 7, if the a.c. values, indicated by 3 are equal. Fig. 7 shows the actual apparatus set up in a copper box, containing two compartments. The lower compartment contains the transmitter and the upper compartment contains the L e c h e r bridge of Fig. 6. The numbering of the different parts in Fig. 7

corresponds to that of Fig. 6. Some results, obtained by this apparatus were:

Wavelength cm	Thermocouple 6 (mA)	Instrument 7 (mA)	Error of 6
114	6,72	6,65	+1,0%
114	5,45	5,35	+1,8%
114	7,60	7,55	+0,7%
90	6,04	6,00	+0,7%
90	7,30	7,20	+1,4%
78	5,19	5,32	—2,5%
78	7,13	7,30	—2,4%
60	5,69	5,95	—4,6%
60	5,28	5,53	—4,7%

The thermocouple 6 was the couple Th_1 of Fig. 4. The d.c. calibration-curve of this couple was used in obtaining the above current values. At a wavelength of 60 cm the difficulty of adjusting the currents through the two thermocouples 3 of Fig. 7 at equal values was rather great with the apparatus in use. We cannot say at present whether the deviations of about 5% at 500 megacycles/sec. are due to the couple 6 or to errors in the adjustment of the currents in the bridge. It is hoped to extend these measurements to higher frequencies and to make them more accurate by means of a newly constructed apparatus.

In connection with the happy circumstance that this article will appear shortly before Prof. Planck's 80th birthday (April 23rd), it is a great pleasure for us, to express our most profound admiration for his important contribution to the development of physical knowledge and to the general worldpicture of mankind.

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REFERENCES

1) L. B. Arguimbau, A high frequency voltage standard. The General Radio Experimenter **12**, Nr. 1, p. 1–3, Jan. 1937.

2) H. E. M. Barlow, A valve ammeter for the measurement of small alternating currents of radiofrequency. J. Inst. el. Eng. London **77**, 612–617, 1935.

3) C. L. Fortescue, The theory and design of hot-wire ammeters for frequencies of 25 to 100 megacycles. J. Inst. el. Eng. London **79**, 179–193, 1936.

4) H. Hoyer, Über die Eichung von Strommessern im Frequenzbereich von 3.10^6 bis $3{,}75 \,.\, 10^7$ Hz mittels Pyrometers. Phys. Z. **38**, 602–609, 1937.
5) J. H. Miller, Thermocouple ammeters for ultrahigh frequencies. Proc. Inst. Radio Eng. **24**, 1567–1572, 1936.
6) A. Scheibe, Über ein hochempfindliches Hitzdrahtluftthermometer zur Messung der Schwingungsenergie kurzer elektrischer Wellen. Jahrb. drahtl. Telegraphie. **25**, 12–16, 1925.
7) H. M. Turner and P. C. Michel, An electrodynamic ammeter for use at frequencies from one to hundred megacycles. Proc. Inst. Radio Eng. **25**, 1367–1374, 1937.
8) J. D. Wallace and A. H. Moore, Frequency errors in radio frequency ammeters. Proc. Inst. Radio Eng. **25**, 327–339, 1937.
9) G. A. Whipple, Electrical measuring instruments. J. Inst. el. Eng. **80**, 195–202, 1937.
10) M. J. O. Strutt, Moderne Mehrgitterelektronenröhren I, Berlin, Springer, 1937.